

IPPP/06/87  
DCPT/06/174

# Inferring Neutrino Cross Sections Above $10^{19}$ eV

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## Abstract

Extremely high energy neutrinos propagating in the atmosphere or in the Earth can originate horizontal or upgoing air-showers, respectively. We calculate the acceptances (event rate/flux) for detecting both types of events by fluorescence detectors, both space-based as with the EUSO and OWL proposals, and ground-based, as with Auger, HiRes and Telescope Array. We depict them as a function of the neutrino-nucleon cross section,  $\sigma_{\nu N}^{CC}$ , and show that from the ratio of these two classes of events, the inference of  $\sigma_{\nu N}^{CC}$  above  $10^{19}$  eV appears feasible, assuming that a neutrino flux exists at these energies. Our semi-analytic calculation includes realistic energy-losses for tau leptons and Earth-curvature effects. We also consider constraints on shower development and identification and the effects of a cloud layer.

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## 1. Introduction

Above the Greisen-Zatsepin-Kuzmin (GZK) energy of  $E_{\text{GZK}} \sim 5 \times 10^{19}$  eV [1] ultra-high energy neutrinos are probably the only propagating primaries. Moreover, in contrast to cosmic-rays, they point back to their astrophysical sources carrying information not accesible with other primaries. The detection of ultra-high energy neutrinos also allows studies of the fundamental properties of neutrinos themselves, as for instance the neutrino-nucleon cross section at energies beyond the reach of our terrestrial accelerators.

In this talk, based on Ref. [2], we study the potential for cosmic-ray experiments designed to track ultra-high energy air-showers by monitoring their fluorescence yield, to detect horizontal air-showers (HAS) and upgoing air-showers (UAS) induced by a cosmic neutrino flux and show the ability of these experiments to infer the neutrino-nucleon cross section,  $\sigma_{\nu N}^{CC}$ , at energies above  $10^{19}$  eV, from the ratio of their UAS and HAS events. Such energies are orders of magnitude beyond the energies accessible to man-made terrestrial accelerators. From the point of view of QCD, such a cross section measurement would be an interesting microscope into the world of small-x parton evolution. Deviations from QCD-motivated extrapolations [3] could reduce the cross section due to saturation effects [4] or enhance it by the existance of new physics thresholds [5].

In Ref. [6] it was shown that by comparing the HAS and UAS event rates the neutrino-nucleon cross section may be inferred. The calculation of Ref. [6] gave an approximate result for the dependence of the UAS event rates on the neutrino-nucleon cross section. In this talk, following the results of Ref. [2], we improve upon Ref. [6] in several ways, as we show below. On the other hand, the prospects of inferring the neutrino-nucleon cross section at neutrino telescopes such as IceCube or at the Auger observatory have been studied in Ref. [7].

## 2. Air-shower rates and constraints on shower-development

Ultra-high energy neutrinos are expected to arise from the decay of pions and subsequently muons produced in astrophysical sources [8] (for the case of production from neutron decays see, eg, Ref. [9]). After propagating for many oscillation lengths and due to the maximal mixing between  $\nu_\mu$  and  $\nu_\tau$  inferred from terrestrial oscillation experiments, all flavors are populated. Thus, a detector optimized for  $\nu_e$  or  $\nu_\mu$  or  $\nu_\tau$  can expect a measurable flux from cosmic neutrinos.

The weak nature of the neutrino-nucleon cross section means that HAS begin low in the atmosphere, where the target is most dense, and thus that the event rate for neutrino-induced HAS is proportional to the cross section. Following Ref [2], for the case of HAS event rates we will only consider  $\nu_e$  charged current interactions.

For a neutrino-induced UAS, the dependence on the neutrino cross section is more complicated. The Earth itself is opaque for neutrinos with energies exceeding about a PeV of energy. However, “Earth-skimming” neutrinos, those with a short enough chord length through the Earth, will penetrate and exit, or penetrate and interact. In particular, there is much interest in the Earth-skimming process  $\nu_\tau \rightarrow \tau$  in the shallow Earth, followed by  $\tau$  decay in the atmosphere to produce an observable shower. In Ref. [6] it was shown that the rate for the Earth-skimming process  $\nu_\tau \rightarrow \tau$  is *inversely* proportional to  $\sigma_{\nu N}^{CC}$ . The inverse dependence of UAS rate on  $\sigma_{\nu N}^{CC}$  is broken by the  $\tau \rightarrow \text{shower}$  process in the atmosphere. As the cross section decreases, the allowed chord length in the Earth increases, and the tau emerges with a larger angle from the Earth’s tangent plane. This in turn provides a smaller path-length in air in which the tau may decay and the resulting shower may evolve. This effect somewhat mitigates the inverse dependence of the UAS on  $\sigma_{\nu N}^{CC}$ .

The main aim of the study in Ref. [2] was to provide a detailed and improved extension of the idea introduced in Ref. [6]. Hence, here we include the energy dependences of the tau energy-losses in the Earth, and of the tau lifetime in the atmosphere. For the energy-losses, we distinguish between tau propagation in rock and in water. In the case of the UAS, the pathlength of the pre-decayed tau may be so long that the Earth’s curvature represents a non-negligible correction, that we include. We also consider the partial loss of visibility due to cloud layers. On the issue of shower development, we incorporate the dependence of atmospheric density on altitude and add some conditions for the showers to be observable. Shower detection will require that within the field of view, the length of the shower track projected on a plane tangent to the Earth’s surface exceeds some minimum length,  $l_{\min}$ . In addition, a minimum column density,  $d_{\min}$ , beyond the point of shower initiation is required for the shower to develop in brightness. On the other hand, after a maximum column density,  $d_{\max}$ , the shower particles are below threshold for further excitation of the  $N_2$  molecules which provide the observable fluorescence signal. Therefore, visible showers end at  $d_{\max}$ . Finally, the fluorescent emission per unit length of the shower will decline exponentially with the air density at altitude. We will take  $z_{\text{thin}} = 24$  km as the altitude beyond which the signal becomes imperceptible. Regarding the choice of  $d_{\min}$  and  $d_{\max}$ , they are inferred from the observed longitudinal development profiles of ultrahigh-energy cosmic ray showers. On the other hand, we assign a relatively small value to  $l_{\min}$  to maximize the observable event rate. For a summary of the different values adopted to obtain the results, full details on the analytic description of the effects of these parameters on the event rates and comparison with prior work, we defer the reader to Ref. [2].

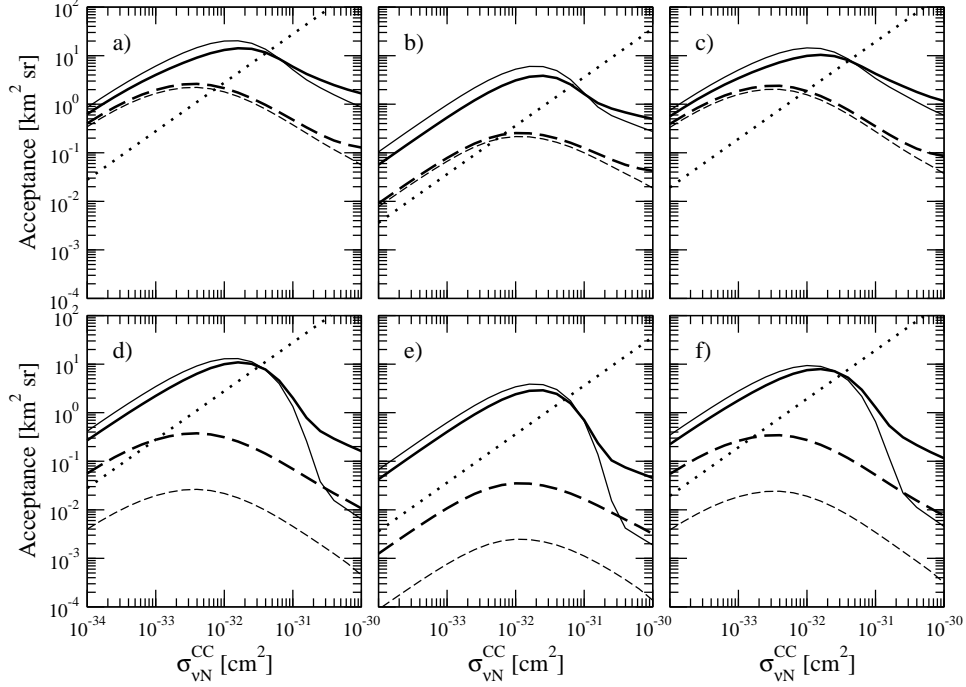


Fig. 1. Acceptances with  $l_{\min}$  fixed at 5 km,  $d_{\min}$  at 400g/cm<sup>2</sup>, and  $d_{\max}$  at 1200g/cm<sup>2</sup>. The curves correspond to HAS (dotted line) and UAS over ocean with  $E_\nu = 10^{21}$  eV (thick solid line), ocean with  $E_\nu = 10^{20}$  eV (thin solid line), land with  $E_\nu = 10^{21}$  eV (thick dashed line), and land with  $E_\nu = 10^{20}$  eV (thin dashed line). Panels are for (a) space-based (or ground-based) detectors in the absence of clouds with  $E_{\text{th}}^{\text{sh}} = 10^{19}$  eV; (b) ground-based detectors in the presence of a cloud layer at  $z_{\text{cloud}} = 2$  km with  $E_{\text{th}}^{\text{sh}} = 10^{19}$  eV; (c) spaced-based detectors in the presence of a cloud layer at  $z_{\text{cloud}} = 2$  km with  $E_{\text{th}}^{\text{sh}} = 10^{19}$  eV; (d) space-based (or ground-based) detectors in the absence of clouds with  $E_{\text{th}}^{\text{sh}} = 5 \times 10^{19}$  eV; (e) ground-based detectors in the presence of a cloud layer at  $z_{\text{cloud}} = 2$  km with  $E_{\text{th}}^{\text{sh}} = 5 \times 10^{19}$  eV; (f) spaced-based detectors in the presence of a cloud layer at  $z_{\text{cloud}} = 2$  km with  $E_{\text{th}}^{\text{sh}} = 5 \times 10^{19}$  eV.

### 3. Results

In this section, we present the results of our semi-analytical approach and take the product of area and solid angle  $\sim 10^6$  km<sup>2</sup> sr, i. e. that of the EUSO design report [10].

In Fig. 1 are plotted UAS (solid and dashed) and HAS (dotted) acceptances in units of (km<sup>2</sup>-sr), versus fixed values of  $\sigma_{\nu N}^{\text{CC}}$ . Within the approximations followed in Ref. [2], for the ideal case of a cloudless sky (panels a and d) there is no difference between the acceptances for ground-based and space-based detectors. However, there are significant up-down differences when the sky is covered by clouds (panels b, c, e and f). In this latter case, we model the cloud layer as infinitely thin with altitude  $z_{\text{cloud}}$ , but with an infinite optical depth so that showers are completely hidden on the far side of the cloud layer.

The HAS acceptances depend on neutrino energy only via  $\sigma_{\nu N}^{\text{CC}}(E_\nu)$ , and rise linearly with  $\sigma_{\nu N}^{\text{CC}}$ . Plotted against fixed  $\sigma_{\nu N}^{\text{CC}}$ , then, the straight-line HAS curves (dotted) are universal curves valid for any  $E_\nu$  exceeding the trigger threshold  $E_{\text{th}}^{\text{sh}}$ . The UAS acceptances have a complicated dependence on  $E_\nu$ ; it arises from the energy dependences of  $\nu$  propagation in the Earth, tau propagation in the Earth, and

path-length of the tau in the atmosphere before it decays, the latter also affecting the visible shower characteristics. We can clearly see that the UAS acceptance (and so also the rate) is typically an order of magnitude larger when neutrinos traverse a layer of ocean water, compared to a trajectory where they only cross rock. Thus, the UAS event rate is enhanced over the ocean relative to over land. The value of this enhancement depends on the shower threshold-energy  $E_{\text{th}}^{\text{sh}}$  of the detector (upper versus lower panels) and on the neutrino-nucleon cross section in a non-trivial way. On the other hand, quantitatively, the ground-based acceptances are quite reduced by the low-lying clouds, whereas the space-based acceptances are not, as one would expect. The suppression of the ground-based acceptance is most severe for small cross sections, for which the tau leptons emerge more vertically and disappear into the clouds before their eventual shower occurs and develops. Ground-based UAS acceptances are reduced by up to an order of magnitude over water, and even more over land. Ground-based HAS acceptances are reduced by an order of magnitude. For space-based detectors, the UAS acceptance is reduced little by clouds at 2 km. Larger neutrino cross sections lead to more tangential tau-showers which may hide below a low-lying cloud layer. We see that UAS reductions are a factor of 2 for the larger cross sections shown, and less for the smaller values of cross section.

We obtain benchmark event rates by multiplying our calculated acceptances with a benchmark integrated flux of one neutrino per  $(\text{km}^2 \text{ sr yr})$ . The result is a signal exceeding an event per year for an acceptance exceeding a  $(\text{km}^2\text{-sr})$ . Thus we see that this benchmark flux gives a HAS rate exceeding 1/yr if  $\sigma_{\nu N}^{\text{CC}}$  exceeds  $10^{-32} \text{ cm}^2$ ; and an UAS rate exceeding 1/yr over water for the whole cross section range with  $E_{\text{th}}^{\text{sh}} = 10^{19} \text{ eV}$ , and over land if  $\sigma_{\nu N}^{\text{CC}} \lesssim 10^{-31} \text{ cm}^2$ . When  $E_{\text{th}}^{\text{sh}}$  is raised, however, the UAS signal over land is seriously compromised, while UAS rates over the ocean are little changed, HAS rates are unchanged, as long as  $E_{\text{th}}^{\tau}$  exceeds  $E_{\nu}$ .

We call attention to the fact that for UAS over both ocean and land, there is a maximum in the UAS acceptance at cross section values  $\sigma_{\nu N}^{\text{CC}} \sim (1 - 2) \times 10^{-32} \text{ cm}^2$  and  $\sigma_{\nu N}^{\text{CC}} \sim (0.3 - 0.5) \times 10^{-32} \text{ cm}^2$ , respectively. For cross sections similar or smaller than those at the maximum, the acceptance for UAS is larger than that for HAS; conversely, for cross sections above those at the maximum, HAS events will dominate UAS events. The cross section value at the maximum lies just below the extrapolation of the Standard Model cross section, which for the two initial neutrino energies considered,  $10^{20} \text{ eV}$  and  $10^{21} \text{ eV}$ , is  $0.54 \times 10^{-31} \text{ cm}^2$  and  $1.2 \times 10^{-31} \text{ cm}^2$ , respectively. If this extrapolation is valid, then one would expect comparable acceptances (and event rates) for UAS over water and for HAS. If the true cross section exceeds the extrapolation, then HAS events will dominate UAS events; if the true cross section is suppressed compared to the extrapolation, then UAS events will dominate HAS events. Importantly, the very different dependences on the cross section of the HAS and UAS acceptances offers a practical method to measure  $\sigma_{\nu N}^{\text{CC}}$ . One has simply to exploit the ratio of UAS-to-HAS event rates. Furthermore, the shape of the UAS acceptance with respect to  $\sigma_{\nu N}^{\text{CC}}$  establishes the “no-lose theorem” [2,6], which states that although a large cross section is desirable to enhance the HAS rate, a smaller cross section still provides a robust event sample due to the contribution of UAS. The latter is especially true over ocean.

## 4. Conclusions

In this talk we have presented a mostly analytic calculation of the acceptances of space-based and ground-based fluorescence detectors of air-showers at ultra-high energies. Included in the calculation are the dependences of the acceptances on initial neutrino energy, trigger-threshold for the shower energy, composition of Earth (surface rock or ocean water), and several shower parameters (the minimum and maximum column densities for shower visibility, and the tangent length of the shower). Also included in the calculation are suppression of the acceptances by cloud layers and by the Earth's curvature. And most importantly, also included are the dependences on the unknown neutrino-nucleon cross section. The dependence is trivial and linear for HAS, but nontrivial and nonlinear for UAS.

The merits of the analytic construction are two-fold: it offers an intuitive understanding of each ingredient entering the calculation; and it allows one to easily re-compute when different parameters are varied. While a Monte Carlo approach may be simpler to implement, it sacrifices some insight and efficiency.

The differing dependences of HAS and UAS on  $\sigma_{\nu N}^{CC}$  enable two very positive conclusions: (1) the “no-lose theorem” is valid, i. e. that acceptances are robust for the combined HAS plus UAS signal regardless of the cross section value; (2) and an inference of  $\sigma_{\nu N}^{CC}$  above  $10^{19}$  eV is possible if HAS and UAS are both measured.

## Acknowledgments

I would like to thank T. Weiler for enlightning discussions and for a fruitful collaboration.

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